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Effectiveness of RZWQM for Simulating Alternative Great Plains Cropping Systems

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ABSTRACT

The Root Zone Water Quality Model (RZWQM) is a comprehensive agricultural system model with the capacity to predict crop–environmental response to varying soil and crop management systems. Our objective was to evaluate RZWQM for its ability to simulate a 2-yr winter wheat (*Triticum aestivum* L.)–fallow (WF) rotation and a more complex wheat–corn (*Zea mays* L.)–fallow (WCF) rotation under tilled and no-till (NT) conditions on a Weld silt loam soil in semiarid northeastern Colorado. Measured data from all phases of both rotations were compared with simulated values using root mean square error (RMSE) values to quantify the agreement. Soil water in different layers, total soil profile (180 cm) water contents, and grain yield were accurately predicted with RMSEs ranging between 0.055 and 0.061 $m^3 m^{-3}$, 4.6 and 7.1 cm, and 244 and 867 kg ha^{-1}, respectively. Leaf area index (LAI), evapotranspiration, and biomass predictions were less accurate with RMSEs between 0.7 and 1.6 cm^2, 5.5 and 9.7 cm, and 1027 and 2714 kg ha^{-1}, respectively. Greater soil water and crop yield measured for NT compared with conventional tillage (CT) were simulated reasonably well. Predicted soil organic C was greater in the surface 0.10 m for NT compared with CT after 11 yr. Although the crop growth component of RZWQM needs improvement, especially with regard to LAI, we conclude the model has potential for simulating alternative crop rotations in the central Great Plains. One potential application for RZWQM in this region may be to predict viable cropping opportunities for evolving conservation programs such as the Conservation Security Program (CSP).

Cropping systems incorporating summer fallow can store soil water and reduce the chance for subsequent crop failure. These systems dominated agriculture in the Great Plains during the 20th century (Peterson et al., 1993). Until the 1980s, the traditional cropping system was WF(CT) (Black, 1983; Derksen et al., 2002; Norwood, 2000). The WF(CT) cropping system in the semiarid Great Plains can have serious adverse impacts on the soil environment due to increased potential wind and water erosion and subsequent losses of soil organic matter (SOM) and productivity. With CT during the fallow period, soil organic C (SOC) declines through accelerated decomposition and erosion (Bowman et al., 1990; Peterson et al., 1993). Doran et al. (1998) found declining SOC in the 0.00- to 0.08-m and 0.00- to 0.30-m layers with both CT and NT in WF in western Nebraska and concluded that cropping intensification would be necessary to reverse the decline. Studies oriented toward amelioration of adverse impacts of WF(CT) on soil quality and productivity increased substantially throughout the Great Plains in recent years. Numerous research efforts emphasized developing better cropping and tillage practices for optimum use of available rainfall and minimal environmental impact (Halvorson, 1990; Anderson et al., 1999). To develop environmentally sound cropping systems as alternatives to WF(CT), field experiments were established in 1990 on a Weld silt loam soil (fine, smectitic, mesic Aridic Argiustolls) at the Central Great Plains Research Station at Akron, CO. About 20 crop rotations under both CT and NT practices are currently being investigated. To effectively extend research results obtained in those experiments to other soils and climates of the region and to ascertain production risk in highly variable climates such as those found in the Great Plains, tools are needed to synthesize and quantify the overall response. Furthermore, to truly solve real-world problems, accurate tools are needed to help producers and researchers understand the broader agricultural systems issues (Peterson et al., 1993). Weiss and Robb (1988) proposed a computer-based systems approach for synthesizing knowledge bases. Using agricultural systems models to integrate knowledge accrued from soil and crop management research has been proposed (Elliott and Cole, 1989). Conducting field research on all aspects of alternate crop management practices for selection of a viable farming system is hindered by both time and cost. These problems can be addressed by using data from alternative cropping systems studies to calibrate and evaluate agricultural systems models that can subsequently be used for various other management strategies and thus extend the results into various temporal and spatial dimensions (Knisel and Turtola, 2000; Mathews and Blackmore, 1997; Godwin and Jones, 1991; Paz et al., 1998, 1999).

The RZWQM (Hanson et al., 1998; Ahuja et al., 2000) is a process-oriented agricultural system model that integrates various biological, physical, and chemical processes in the soil–plant–atmosphere continuum and simulates the impact and feedback of alternative management practices on crop production and water quality. In RZWQM, the crop component is represented by a generic plant growth model that can be parameterized to simulate spe-

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Abbreviations: C, corn; CT, conventional tillage; ET, evapotranspiration; F, fallow; LAI, leaf area index; NT, no-tillage; PSE, precipitation storage efficiency; RMSE, root mean square error; RZWQM, Root Zone Water Quality Model; SOC, total soil organic carbon; SOM, soil organic matter; W, winter wheat; WCF, wheat–corn–fallow (rotation); WF, winter wheat–fallow (rotation).

cific crops. The generic plant model has been parameterized to simulate corn, soybean (*Glycine max* L.), and wheat and validated against field experimental data (Saseendran et al., 2004, 2005; Ma et al., 2003; Nielsen et al., 2002). Using RZWQM, Saseendran et al. (2004) developed N management strategies for rainfed winter wheat in eastern Colorado. RZWQM has not been evaluated for simulating crop rotation under till and NT practices. Our objectives were to verify and test RZWQM for various wheat, corn, and fallow systems under rainfed conditions and with varying tillage intensities for semiarid northeastern Colorado and to predict changes in surface SOC that would occur over time in the various cropping systems.

MATERIALS AND METHODS

Alternative Crop Rotation Experiment

Data were derived from an alternative crop rotation experiment conducted at the Central Great Plains Research Station, USDA-ARS, Akron, CO (40°09′ N, 103°09′ W, 1384 m) since 1990. In these experiments, various tillage and crop sequences are assessed for effects on productivity, soil and water quality, and economic viability. These experiments were established on a Weld silt loam soil using a randomized complete block design with three replications. Detailed descriptions of the tillage, plot area, and experimental design for the experiment were reported by Bowman and Halvorson (1997) and Anderson et al. (1999). Plots (9.1 by 30.5 m) were laid out in an east–west direction. Twenty crop rotations involving combinations of six crops and fallow and three tillage treatments were established. In the present study, we have used data from only the WF(CT), WF(NT), and WCF(NT) crop rotation systems from 1992 to 2002. All phases of each rotation were present every year. As such, the data used in this study comprise a total of seven data sets of 10- to 11-yr duration each: (i) WF(CT)-F (beginning fallow phase in 1992), (ii) WF(CT)-W (beginning wheat phase in 1992), (iii) WF(NT)-F (beginning fallow phase in 1992), (iv) WF(NT)-W (beginning wheat phase in 1992), (v) WCF(NT)-W (beginning wheat phase in 1992), (vi) WCF(NT)-C (beginning corn phase in 1992), and (vii) WCF(NT)-F (beginning fallow phase in 1992). The CT system consisted of four to eight sweep plow operations as needed to control weeds during fallow. Contact and residual herbicides were used to control weeds in the NT system. Fertilizer N application rates were based on annual soil tests, a winter wheat yield goal of 2688 kg ha^{-1}, and a corn yield goal of 4100 kg ha^{-1}. Actual fertilizer applied for different crops in different crop sequences over different rotation phases and years ranged between 34 and 95 kg N ha^{-1} for corn and between 12 and 67 kg N ha^{-1} for winter wheat. Fertilizer N as ammonium nitrate was surface-broadcast before planting of winter wheat and corn from 1992 to 1996 and banded at planting from 1997 to 2001. All the crops were grown under rainfed conditions. Wheat planting occurred between 18 and 26 September, and corn planting occurred between 29 April and 18 May in individual crop years. An average seeding density of 2 223 000 seeds ha^{-1} for wheat and 39 520 seeds ha^{-1} for corn was used in all the model simulations. Wheat cultivar ‘TAM 107’ was used for the 1992 to 1996 crops, and ‘Akron’ was planted for the 1997 to 2001 crops. Corn hybrids planted were ‘Pioneer Hybrid 3732’ from 1992 to 1997, ‘DK493 BT’ in 1998 and 1999, ‘DKC49-92’ in 2000, and ‘NK4242 BT’ in 2001. Winter wheat harvest occurred between 21 June and 27 July, and corn harvest occurred between 18 September and 27 October of individual years.

Soil water measurements were made with a neutron probe at two locations near the center of each plot at depths of 45, 75, 105, 135, and 165 cm. Time-domain reflectometry was used to measure soil water in the 0- to 30-cm depth. Measured soil water from the surface to 180-cm depth was used for calculating crop evapotranspiration (ET) employing the water balance method, assuming deep percolation and runoff losses in the experimental plots were negligible. Daily rainfall, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity recorded by an automated weather station at the research station provided input for model simulations. Mean annual precipitation received over the study region is about 420 mm with about 80% of the total falling during April to September. Precipitation recorded at the station during the experimental period (1992–2001) exhibited high interannual variability in amount and temporal distribution (Table 1). From 1992 to 2001, total precipitation received yearly ranged from 305 mm in the year 1998 to 524 mm in 1995. During April to June (crop growth period for winter wheat), precipitation received ranged between 53 mm in 1998 and 328 mm in 1995. During May to September (crop growth period for corn), precipitation recorded at the site varied between 143 mm 1994 and 418 mm in 1996.

Model simulations of four crop rotation phases with beginning fallow or beginning corn phase in 1992 [WCF(NT)-C, WCF(NT)-F, WF(CT)-F, and WF(NT)-F] were started on 1 Jan. 1992. The three crop rotations in the beginning wheat phase in 1992 [WCF(NT)-W, WF(CT)-W, and WF(NT)-W] were simulated from 1 Jan. 1991 with the wheat planted in September 1991. Initial soil water contents in the simulations were assumed to be at field capacity.

Table 1. Monthly total precipitation received at the experimental site during 1992 to 2001.

Month	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	1992–2001	1908–2001
	mm											
January	14	6	10	22	8	13	1	2	6	22	10	9
February	5	14	5	9	1	13	32	4	8	11	10	9
March	50	13	2	22	29	2	4	8	40	25	20	21
April	6	47	53	62	12	22	18	52	41	34	35	42
May	57	27	29	145	116	55	25	80	20	107	66	76
June	79	45	6	121	65	80	10	62	19	34	52	62
July	53	114	70	39	83	31	102	40	66	67	67	69
August	102	24	30	20	68	62	56	173	55	58	65	53
September	1	23	8	57	86	25	8	39	39	44	33	31
October	21	95	73	10	12	59	17	12	49	17	37	23
November	19	26	26	15	1	7	27	12	8	5	15	14
December	6	12	13	2	1	11	5	15	6	0	7	10
Total yearly	413	446	325	524	482	380	305	499	357	424	416	420
Total March–June	197	132	90	350	222	159	57	202	120	200	173	201
Total May–Sept.	292	233	143	382	418	253	201	394	199	310	283	292

Model Description

RZWQM is a comprehensive agricultural system model designed to predict crop–environmental responses to alternative management systems (Ahuja et al., 2000). Potential ET in the soil–residue–canopy system is modeled using the "extended Shuttleworth–Wallace ET model" (Farahani and Ahuja, 1996). Water infiltration is calculated with the Green–Ampt equation (Green and Ampt, 1911), and water redistribution is calculated by solving the Richards' equation. Soil hydraulic properties are estimated using the Brooks–Corey equation (Brooks and Corey, 1964). The OMNI computer program drives the organic matter/N cycling in RZWQM (Shaffer et al., 2000). RZWQM has a generic crop model (Hanson, 2000) that can be parameterized to simulate a specific crop. The plant model simulates both plant population development (number of plants dying, remaining in a given growth stage, or moving to the next growth stage) and plant growth. Phenological development, while not explicitly simulated, is handled through seven growth stages. These include: (i) dormant seeds, (ii) germinating seeds, (iii) emerged plants, (iv) established plants, (v) plants in vegetative growth, (vi) reproductive plants, and (vii) senescent plants. Detailed descriptions of the different components of the RZWQM are available elsewhere (Ahuja et al., 2000; Hanson et al., 1998). Management practices such as tillage; applications of manure, fertilizers, and pesticides; planting and harvesting operations; irrigation; and surface crop residue dynamics are simulated in the model. These processes are simulated through changing soil properties or change in the state of the system. Tillage is assumed to destroy all the macropores in the tillage zone. Tillage-induced bulk density change is modeled following the procedure used in the EPIC model (Williams et al., 1984). Change in bulk density affects soil porosity or saturated soil water content, soil water content–suction relationships, and hydraulic conductivity. In RZWQM, the presence of a surface residue layer is modeled to benefit soil water storage by affecting the potential soil evaporation process in the extended Shuttleworth–Wallace ET model (Farahani and Ahuja, 1996). Surface residue is also a potential source for C and N in the soil nutrient cycle (Rojas and Ahuja, 2000). Detailed descriptions of these simulations are available elsewhere (Ahuja et al., 2000).

Table 2. Calibrated physical and hydraulic properties of the Weld silt loam soil used in the model simulations.

Soil depth	Soil bulk density	Sand	Silt	Clay	Water content 33 kPa	Water content 1500 kP	Saturated hydraulic conductivity
m	Mg m^{-3}		%			m^3 m^{-3}	mm h^{-1}
0.00–0.15	1.33	39.0	41.7	19.3	0.224	0.092	96.7
0.15–0.30	1.33	32.3	44.3	23.4	0.236	0.104	96.7
0.30–0.60	1.32	37.0	40.7	22.3	0.230	0.098	96.7
0.60–0.90	1.36	45.7	36.7	17.6	0.221	0.089	140.8
0.90–1.20	1.40	45.7	42.3	12.0	0.215	0.084	118.7
1.20–1.50	1.42	48.3	41.7	10.0	0.212	0.081	108.0
1.50–1.80	1.42	48.3	41.7	10.0	0.212	0.081	108.0

Model Parameterization and Calibration

For accurate simulations, RZWQM must be calibrated for soil hydraulic properties, nutrient properties, and plant growth parameters for the site and crops being simulated (Hanson et al., 1999). We followed the detailed procedures for calibrating the RZWQM as laid out by Hanson et al. (1999) and Ahuja and Ma (2002).

For simulation of the soil water balance in RZWQM, each soil horizon is defined in terms of physical (bulk density, particle density, porosity, and texture) and hydraulic properties. Hydraulic properties are defined using the Brooks and Corey (1964) equations with slight modifications (Ahuja et al., 2000). The Brooks–Corey parameters compiled by Rawls et al. (1982) for 11 soil textural classes are available in the model database if measured values are not available. We did not have field measurements of soil physical and hydraulic properties, so simula-

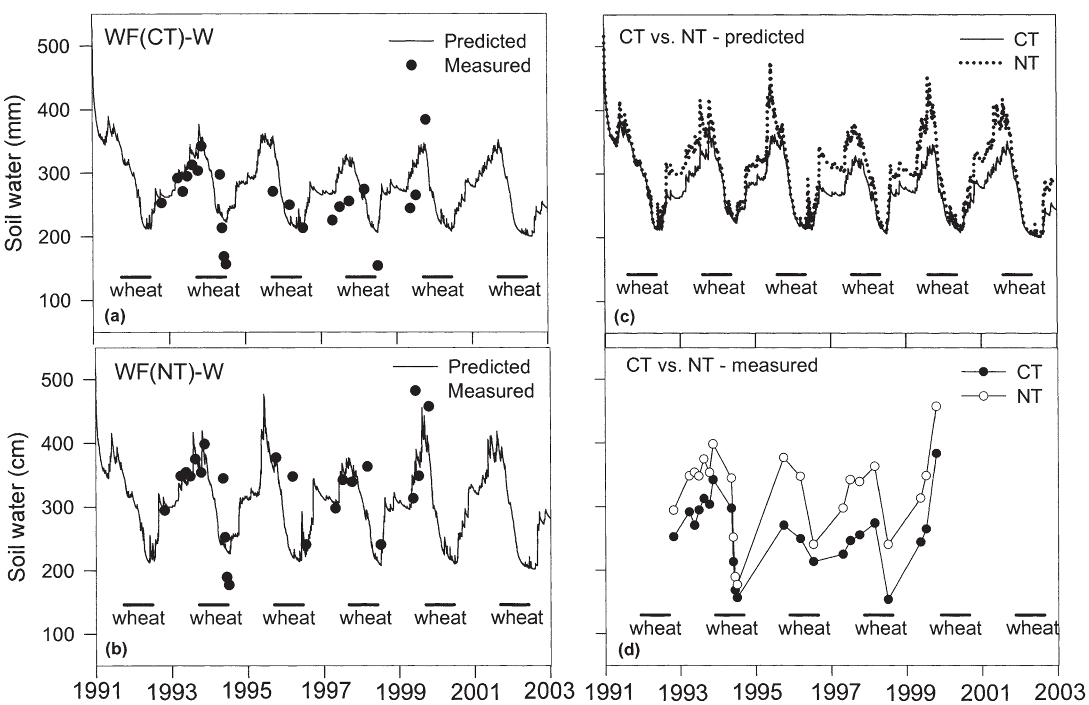

Fig. 1. Measured and predicted (RZWQM) total profile (180 cm) soil water under wheat fallow (WF) for the beginning wheat data set: (a) conventional tillage (CT), (b) no-till (NT), (c) comparison of predicted soil water under WF(CT) and WF(NT), and (d) comparison of measured soil water under WF(CT) and WF(NT).

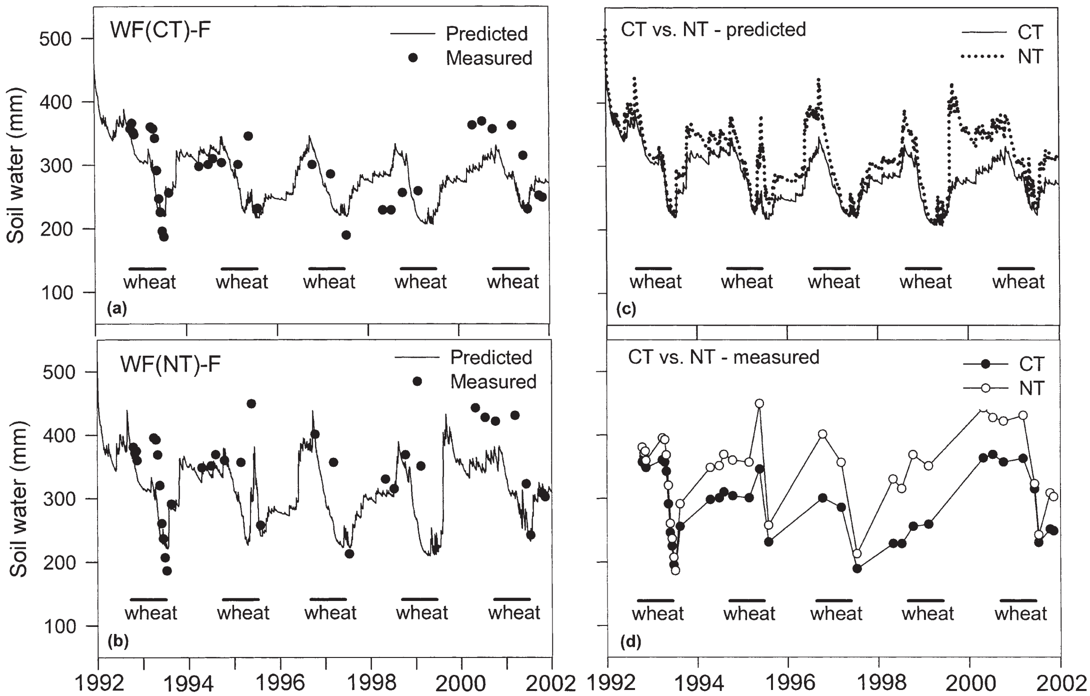

Fig. 2. Measured and predicted (RZWQM) total profile (180 cm) soil water under wheat fallow (WF) for the beginning fallow data set: (a) conventional tillage (CT), (b) no-till (NT), (c) comparison of predicted soil water under WF(CT) and WF(NT), and (d) comparison of measured soil water under WF(CT) and WF(NT).

tions were made using literature values for the location. However, predicted soil water content did not match the measured values. Better agreement between simulated and measured soil water content was obtained using default soil physical properties and the Brooks–Corey parameters describing soil hydraulic properties, available in the model database for loam soils (Table 2). Measured soil water data from the WCF(NT)-F rotation were used to calibrate soil water content.

The model requires establishment of initial C/N pool sizes for the fast and slow residue pools; slow, medium, and fast humus pools; and the three microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs) (Hanson et al., 1999). No laboratory procedures were known to effectively determine the sizes of these pools (Ahuja and Ma, 2002). Therefore, because previous management at a site determines the initial state of a soil in terms of its organic matter and microbial populations, simulations with previous management practices will usually create a better initial condition for these parameters (Ma et al., 1998). Hanson et al. (1999) suggested 5- to- 7-yr runs for short-term stability of the SOM pool sizes

Table 3. Average deviation (root mean square error) between predicted and observed evapotranspiration (ET), leaf area index (LAI), grain yield, biomass, and soil water content.

Cropping system†	ET	LAI	Grain yield	Biomass	Soil water	Total profile (180 cm) soil water
	m	$m^2\ m^{-2}$	— kg ha^{-1} —		$m^3\ m^{-3}$	mm
WF(CT)-W	56	1.35	326	2714	0.058	53
WF(NT)-W	97	0.70	244	1859	0.057	56
WF(CT)-F	97	1.63	517	1771	0.055	46
WF(NT)-F	55	0.85	698	2488	0.058	61
WCF(NT)-W	68	0.99	867	1578	0.060	56
WCF(NT)-C	72	1.37	803	1027	0.061	71
WCF(NT)-F	44	1.05	618	1566	0.060	55

† WF(CT)-W = conventionally tilled wheat–fallow beginning with the wheat phase; WF(CT)-F = conventionally tilled wheat–fallow beginning with the fallow phase; WF(NT)-W = no-till wheat–fallow beginning with the wheat phase; WF(NT)-F = no-till wheat–fallow beginning with the fallow phase; WCF(NT)-W = no-till wheat–corn–fallow beginning with the wheat phase; WCF(NT)-C = no-till wheat–corn–fallow beginning with the corn phase; WCF(NT)-F = no-till wheat–corn–fallow beginning with the fallow phase.

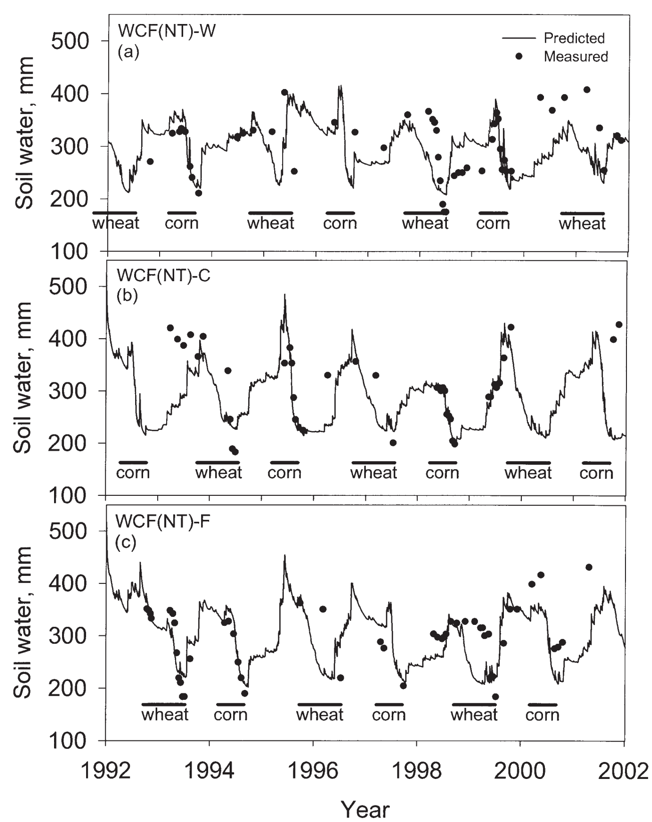

Fig. 3. Comparison between measured and RZWQM-predicted total profile (180 cm) soil water under wheat–corn–fallow no-till [WCF(NT)] beginning with (a) wheat, (b) corn, and (c) fallow phases in 1992.

Table 4. Comparison between measured and simulated wheat evapotranspiration (ET) under conventional till (CT) and no-till (NT) wheat–fallow (WF) systems.

Year	CT Measured	CT Simulated	CT Difference	NT Measured	NT Simulated	NT Difference	Increase of ET in NT over CT Measured	Increase of ET in NT over CT Simulated
	mm	mm	%	mm	mm	%	%	%
Beginning fallow data set								
1993	376	291	23	394	310	21	5	7
1995	648	497	23	660	628	5	2	27
1997	312	277	11	386	334	13	24	20
1999	333	274	18	361	341	6	8	24
2001	411	300	27	462	396	14	12	32
Beginning wheat data set								
1994	384	284	26	419	296	29	9	4
1996	356	354	1	442	424	4	24	20
1998	269	254	6	348	286	18	29	13
2000	312	263	16	348	311	11	11	18

and 20 or more years for long-term stability. As recommended by Ahuja and Ma (2002), we began by estimating the three humus organic matter pool sizes at 5, 10, and 85%, respectively, for fast, medium, and slow pools and set the microbial pools at 50 000, 500, and 5000 organisms g^{-1} soil, respectively, for aerobic heterotrophs, autotrophs, and facultative heterotrophs. We ran the model for 85 yr under the WF(CT) rotation to stabilize the SOM pools.

Plant parameters for simulation of winter wheat and corn under the climatic conditions of Akron, CO were calibrated previously by Saseendran et al. (2004) and Saseendran et al. (2005), respectively. In the present study, we made use of these parameters.

The RMSE statistic, which quantifies the average deviation between predicted and observed values, was used to evaluate the simulation results:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

where P_i is the ith predicted value, O_i is the ith observed value, and n is the number of data pairs.

RESULTS AND DISCUSSION

Soil Water, Precipitation Storage Efficiency, and Evapotranspiration Simulations

The RZWQM predicted water content in different soil layers (data not shown) and for the 180-cm soil profile (Fig. 1a, 1b, 2a, and 2b) reasonably well under both CT and NT systems. Soil water predictions For WF(CT) and WF(NT) had RMSE values of 0.058 and 0.057 $m^3\ m^{-3}$, respectively, for the beginning wheat data set, and 0.055 and 0.058 $m^3\ m^{-3}$ for the beginning fallow data set (Table 3). The RMSE values for soil profile (180 cm) water content were 53, 56, 46, and 61 mm, respectively, for WF(CT)-W, WF(NT)-W, WF(CT)-F, and WF(NT)-F data sets (Table 3). Field measurements showed significantly greater ($P < 0.005$, paired t test) soil profile (180 cm) water under NT system compared with the CT system in the WF rotation in both beginning wheat and beginning fallow data sets (Fig. 1d and 2d). Simulations also showed greater soil water content for NT compared with CT ($P <$ 0.005, paired t test) for both data sets (Fig. 1c and 2c), primarily because of reduced evaporation and higher

Table 5. Measured and predicted precipitation storage efficiency (PSE) during the fallow period of conventional till wheat–fallow [WF(CT)], no-till wheat–fallow [WF(NT)], and no-till wheat–corn–fallow [WCF(NT)] systems.

Data set†	Fallow period	Predicted PSE (fraction of precipitation) CT	Predicted PSE (fraction of precipitation) NT	Increase in predicted PSE under NT	Measured PSE (fraction of precipitation) CT	Measured PSE (fraction of precipitation) NT	Increase in measured PSE under NT
				%			%
WF-F	13 July 1993 to 19 Sept. 1994	0.241	0.300	23	0.136	0.235	73
	26 July 1995 to 27 Sept. 1996	0.218	0.321	47	0.125	0.245	96
	12 July 1997 to 21 Sept. 1998	0.220	0.297	35	0.149	0.340	128
	22 June 1999 to 18 Sept. 2000	0.156	0.249	60	0.339	0.410	21
WF-W	11 July 1992 to 20 Sept. 1993	0.174	0.282	62	0.148	0.190	28
	30 June 1994 to 17 Sept. 1995	0.151	0.203	34	0.165	0.289	75
	15 July 1996 to 18 Sept. 1997	0.191	0.264	39	0.080	0.189	137
	2 July 1998 to 22 Sept. 1999	0.150	0.285	89	0.256	0.263	3
	27 June 2000 to 19 Sept. 2001	0.164	0.283	76	0.314	0.380	21
WCF-W	25 Aug. 1993 to 20 Sept. 1994		0.313			0.360	
	19 Aug. 1996 to 19 Sept. 1997		0.278			0.250	
	31 Aug. 1999 to 19 Sept. 2000		0.252			0.382	
WCF-C	30 Aug. 1995 to 28 Sept. 1996		0.322			0.263	
	25 Aug. 1998 to 23 Sept. 1999		0.351			0.364	
WCF-F	19 Aug. 1994 to 26 Sept. 1995		0.247			0.286	
	24 Aug. 1997 to 22 Sept. 1998		0.235			0.324	
	21 Aug. 2000 to 20 Sept. 2001		0.289			0.338	

† WF-F = wheat–fallow beginning with the fallow phase; WF-W = wheat-fallow beginning with the wheat phase; WCF-W = no-till wheat–corn–fallow beginning with the wheat phase; WCF-C = no-till wheat–corn–fallow beginning with the corn phase; WCF-F = no-till wheat–corn–fallow beginning with the fallow phase.

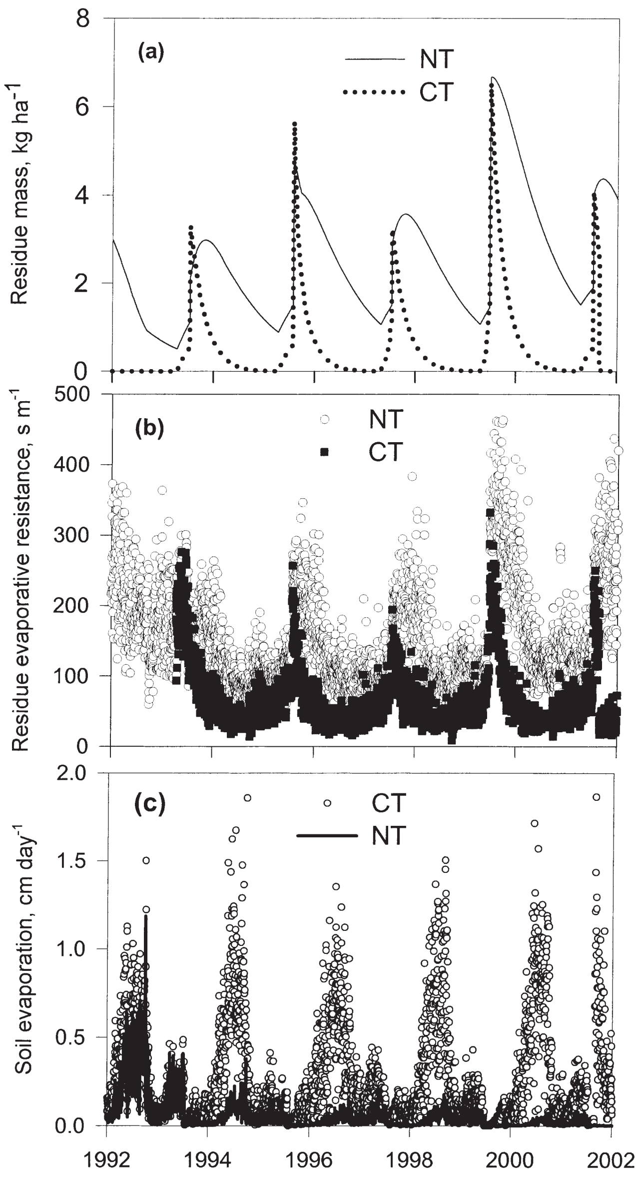

Fig. 4. Model simulations of residue dynamics and residue effects on soil evaporation from conventional till (CT) and no-till (NT) systems in the wheat–fallow cropping system (beginning fallow data set): (a) flat residue mass on the soil surface, (b) residue evaporative resistance, and (c) potential soil evaporation.

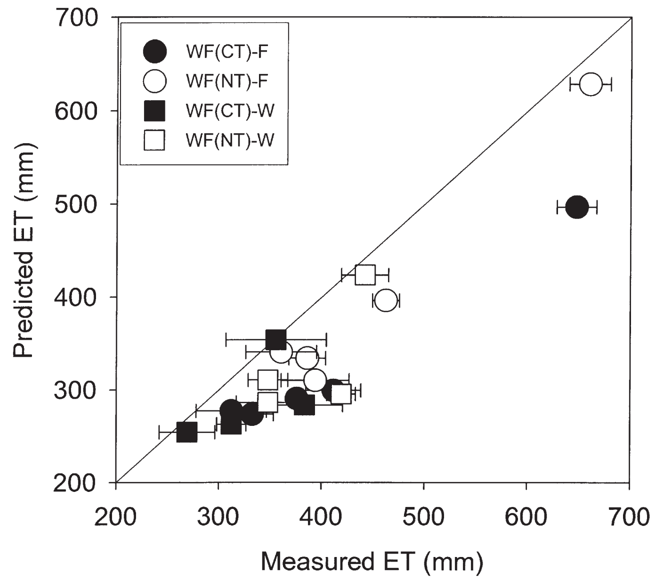

Fig. 5. Comparison between measured and predicted (RZWQM) wheat evapotranspiration (ET) for wheat–fallow (WF) cropping systems in beginning fallow (WF-F) and beginning wheat (WF-W) data sets. Error bars show one standard deviation about the mean of measured ET. CT, conventional till; NT, no-till.

precipitation storage efficiency (PSE). Simulated soil water depletion by wheat water use followed the measured pattern reasonably well during 1991–1992, 1993–1994, 1995–1996, 1997–1998, 1999–2000, and 2001–2002 from the WF(CT)-W and WF(NT)-W data sets (Fig. 1a and 1b) and for 1992–1993, 1994–1995, 1996–1997, 1998–1999, and 2000–2001 from the WF(CT)-F and WF(NT)-F data sets (Fig. 2a and 2b). Extreme soil water depletion during 1993–1994 (second crop season in Fig. 1a and 1b) under both CT and NT was not simulated by the model very well. Overprediction of soil water during the 1993–1994 crop season was caused by simulated ET loss that was 26% lower than measured (Table 4). This led to greater water retention than was actually measured. The model also overpredicted soil water during the 1997–1998 crop season for CT (Fig. 1a), but this time, ET was not underestimated. Another significant error in the predicted soil profile water occurred during 1994–1995 for WF(NT)-F (second crop season in Fig. 2b) when the measured value exceeded the predicted value by 33%.

Predicted water content in different soil layers for all three WCF(NT) data sets showed a comparable degree of accuracy (data not shown). The RMSE values were 0.060, 0.061, and 0.060 $m^3\ m^{-3}$, respectively, under WCF(NT)-W, WCF(NT)-C, and WCF(NT)-F (Table 3). Values of RMSE for soil profile (180 cm) water were 56, 71, and 55 mm, respectively (Table 3). Soil water depletion patterns during the seven crop seasons of the beginning wheat data set (Fig. 3a, the seven crop seasons of the beginning corn data set (Fig. 3b), and the six crop seasons of the beginning fallow data set (Fig. 3c) followed the measured patterns reasonably well. Some of the extreme values in measured soil water [e.g., extreme depletion and recharge during the fifth and seventh crop seasons (Fig. 3a), extreme depletion during the second crop season (Fig. 3b), and extreme depletions and recharge during the first and sixth crop seasons (Fig. 3c)] were not well simulated by the model. These failures were caused by poor predictions of crop biomass and the dynamics controlling residue cover in the NT system and its effect on evaporation. More biomass means more surface residue, less evaporation, and more conservation of soil water. Better predictions of soil water extremes for NT systems will require improving the simulations of biomass and crop residue dynamics.

Increased PSE (fraction of total precipitation stored in the 180-cm soil profile) has been reported with reduced tillage during the summer fallow period (Brandt, 1992; Norwood, 1999) from increased infiltration (Smika and Unger, 1986; Peterson et al., 1993). Destruction of macropores and creation of surface seals from raindrop impact in tilled soils is a significant factor contributing to lower infiltration rates in tilled systems compared with NT systems (Dunn and Phillips, 1991). Simulated PSE during the fallow periods (about 14 mo) between consecutive crops in WF was much higher (23 to 89%) under NT than under CT in both beginning wheat and beginning fallow data sets ($P < 0.005$, paired t test) (Table 5). Predicted PSE ranged from 0.150 to 0.241 and from 0.203 to 0.321 mm mm^{-1} for CT and NT, respectively. Simulated crop residue dynamics showed greater surface residue mass for NT compared with CT (Fig. 4a). Greater residue mass increased resistance to diffusive loss of water vapor as simulated in the ET module of RZWQM (Ahuja et al., 2000) (Fig. 4b). As a result, there were low evaporative losses (Fig. 4c) and greater retention of soil water received following precipitation for NT compared with CT. Interseasonal variation in predicted PSE (Table 5) resulted from variations in the amount and intensity of precipitation received and amount of crop residue left by the preceding crop. Measured increases in PSE under NT compared with CT ranged between 21 and 128% in the WF-F and 3 and 137% in the WF-W data sets (Table 5). Measured PSE for CT and NT in WF ranged from 0.080 to 0.339 and from 0.189 to 0.410 mm mm^{-1}, respectively.

Predicted and measured PSE matched reasonably well for the three WCF(NT) data sets (Table 5). Measured PSE ranged from 0.250 to 0.382 mm mm^{-1} while predicted values ranged from 0.235 to 0.351 mm mm^{-1}. Measured and predicted PSEs in the WCF(NT) system were comparable with those in the WF(NT) system.

Measured wheat ET in WF(NT) was significantly higher ($P < 0.005$, paired t test) than in WF(CT) in both beginning wheat and beginning fallow data sets (Table 4). Model simulations showed a similar increase ($P < 0.005$, paired t test). As discussed above, the model simulated higher PSE and higher available soil water for NT than CT, leading to increased crop growth and higher ET. However, the model generally underpredicted ET for both CT and NT (Fig. 5). The model also simulated deep percolation and runoff losses that were not accounted for in the measured data (data not shown). Therefore, one reason for the apparent underestimate of ET could be water loss through other processes. However, surface runoff was only rarely observed, and soil water measurements did not indicate water movement below the measured soil profile. Measured and predicted increases in ET for WF(NT) over WF(CT) ranged from 2 to 29% and from 4 to 32%, respectively (Table 4).

RZWQM underpredicted ET for all three WCF(NT) data sets (Fig. 6). Deviations between simulated and measured ET ranged from −6 to −32% and from 6 to −23%, respectively, for winter wheat and corn in WCF during the 10-yr period from 1992 to 2001. The apparent underestimation of ET may have been due to overestimation of measured ET due to deep percolation and runoff losses that were not observed or measured.

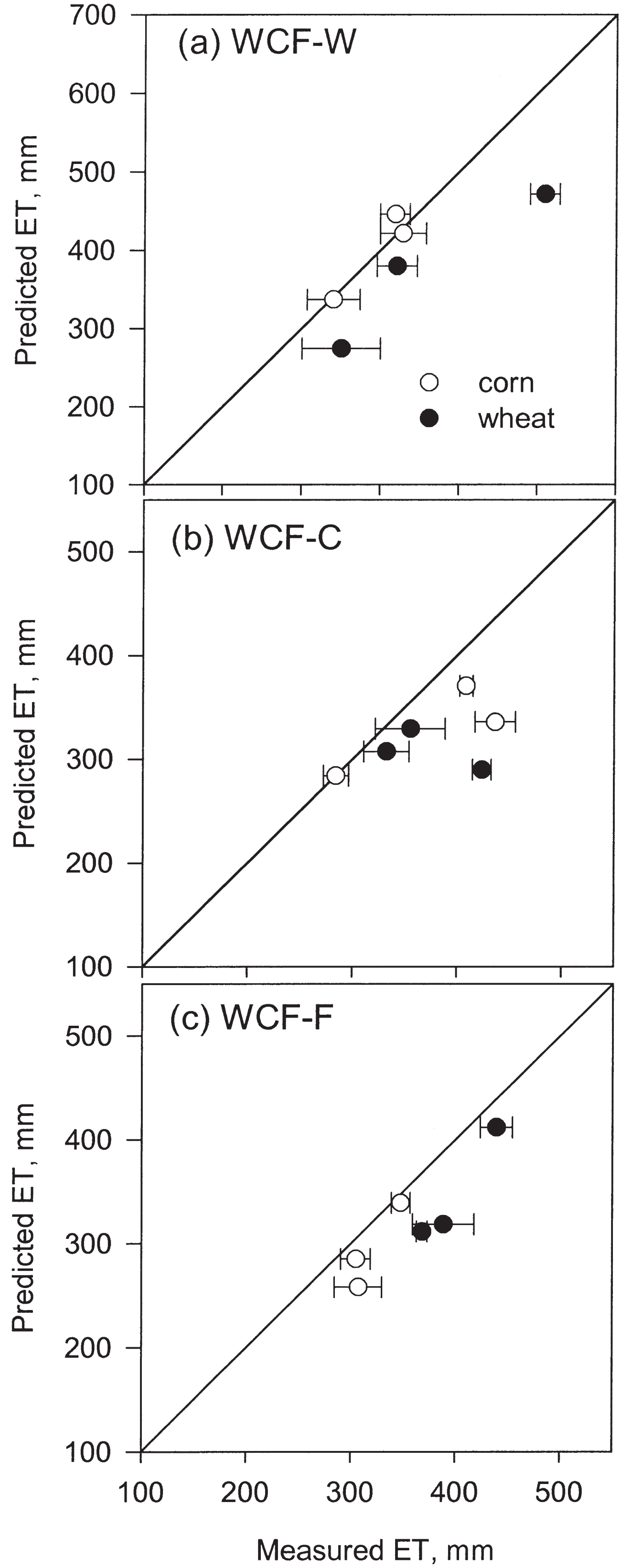

Fig. 6. Comparison between measured and predicted (RZWQM) wheat and corn evapotranspiration (ET) for the wheat–corn–fallow (WCF) cropping system in the beginning wheat (WCF-W), beginning corn (WCF-C), and beginning fallow (WCF-F) data sets. Error bars show one standard deviation about the mean of measured ET.

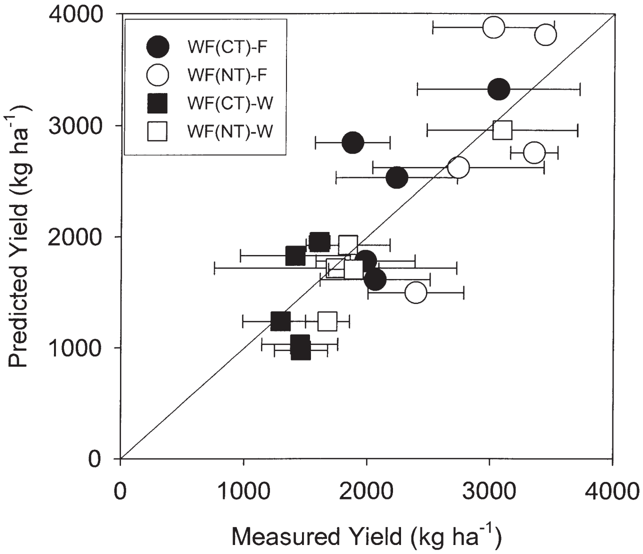

Fig. 7. Comparison between measured and predicted (RZWQM) wheat grain yields for the wheat–fallow (WF) cropping systems in beginning fallow (WF-F) and beginning wheat (WF-W) data sets. Error bars show one standard deviation about the mean of measured yield. CT, conventional till; NT, no-till.

Simulations of Leaf Area Index

Simulations of LAI showed RMSE values of 1.35, 0.70, 1.63, and 0.85 for the WF(CT)-W, WF(NT)-W, WF(CT)-F, and WF(NT)-F data sets, respectively (Table 3). Field measurements of LAI were not continuously available to make detailed analysis of the model simulations, so the RMSEs were calculated based on only 17, 6, 24, and 8 LAI measurements during the 10-yr period (1992–2001). Nonetheless, the results indicate that LAI simulation by the generic plant growth model is poor. Similar poor results were found in the three WCF(NT) data sets (Table 3). Errors in simulations of LAI can cause significant errors in subsequent simulations of dependent processes and parameters (e.g., ET, grain yield, and biomass). Therefore, the generic plant growth model needs further improvement for better leaf area simulations.

Simulations of Grain Yield

Wheat grain yield predictions for both CT and NT were reasonably good (Fig. 7). The RMSEs of predictions were 326, 244, 517, and 698 kg ha^{-1} for WF(CT)-W, WF(NT)-W, WF(CT)-F, and WF(NT)-F data sets, respectively (Table 3). Wheat yield for 11 of 20 crops during the 40 yr of simulation (four data sets, each 10 yr in length) was predicted within one standard deviation of the measured yield (Fig. 7). Four of the data points represent model prediction departures from measured yield of more than 25%. Errors in quantifying water and N stress and the complex interactions between soil water and N were presumably responsible for the large errors. It is difficult to identify a single factor that is solely responsible for the large simulation errors.

Tillage affects grain yield through effects on nutrient and water availability. Better water storage and grain yield associated with NT have been reported (Brandt, 1992). In the present study, measured winter wheat yield in both beginning wheat and beginning fallow data sets of the WF(NT) system was significantly higher than WF(CT) ($P < 0.01$, paired t test). Though at a lower significance level ($P < 0.05$, paired t test), model simulations also showed an increase in grain yield in both beginning wheat and beginning fallow data sets of WF(NT) compared with WF(CT). Simulated increases in biomass and grain yield for NT compared with CT were due to lower soil water stress in response to higher PSE. However, in response to the lower water stress, the NT system also showed higher plant growth and transpiration. This resulted in higher simulated N stress, but it was generally not enough to offset the growth advantages due to low water stress (data not shown). The increase in measured wheat grain yield for NT compared with CT ranged from 12 to 61% for the beginning fallow data set and from 15 to 92% for the beginning wheat

Table 6. Comparison between measured and simulated wheat yield and biomass under conventional till (CT) and no-till (NT) wheat–fallow (WF) systems.

		CT			NT			Increase in NT over CT	
	Year	Measured	Simulated	Difference	Measured	Simulated	Difference	Measured	Simulated
		kg ha^{-1}		%	kg ha^{-1}		%	%	
Grain yield									
Beginning fallow data set	1993	2234	2529	13	3350	2755	−18	50	9
	1995	1983	1779	−10	2394	1495	−38	21	−16
	1997	1874	2843	52	3013	3874	29	61	36
	1999	2062	1612	−22	2734	2621	−4	33	63
	2001	3058	3322	9	3435	3810	11	12	15
Beginning wheat data set	1994	1461	975	−33	1676	1237	−26	15	27
	1996	1608	1949	21	3090	2956	−4	92	52
	1998	1412	1828	29	1740	1716	−1	23	−6
	2000	1294	1238	−4	1887	1705	−10	46	38
	2002	1452	1031	−29	1841	1922	4	27	87
Biomass									
Beginning fallow data set	1993	6660	6123	−8	7336	6465	−12	10	6
	1995	5339	7699	44	4916	7019	43	−8	−9
	1999	4861	7098	46	5601	9750	74	15	37
	2001	9132	7829	−14	9961	8422	−15	9	8
Beginning wheat data set	1994	4475	4563	2	4240	5587	32	−5	22
	1996	4605	6811	48	6596	8168	24	43	20
	1998	2667	6505	144	4300	6128	42	61	−6
	2000	4326	7557	75	5894	8384	42	36	11

data set of the WF system. Simulated increase in grain yield ranged from −16 to 63% and from −6 to 87%, respectively for the two data sets (Table 6). The model failed to predict increased grain yield (21%) for NT compared with CT in the 1994–1995 crop season for the WF-F data set. Instead, it showed a decrease of 16%. Similarly, for the 1997–1998 season, the model predicted a 6% loss in grain yield for NT compared with CT when the measured yield was 23% greater. In these two seasons, N stress simulated for NT was not offset by the increase in water availability and lower water stress. Improvements in the simulations of water and N processes in the model are needed to improve these predictions.

Measured NT wheat yields in the WCF data sets ranged from 1147 to 3535 kg ha^{-1} and were predicted well by the model (Fig. 8). Seven of 10 wheat yield predictions were within one standard deviation of the measured values.

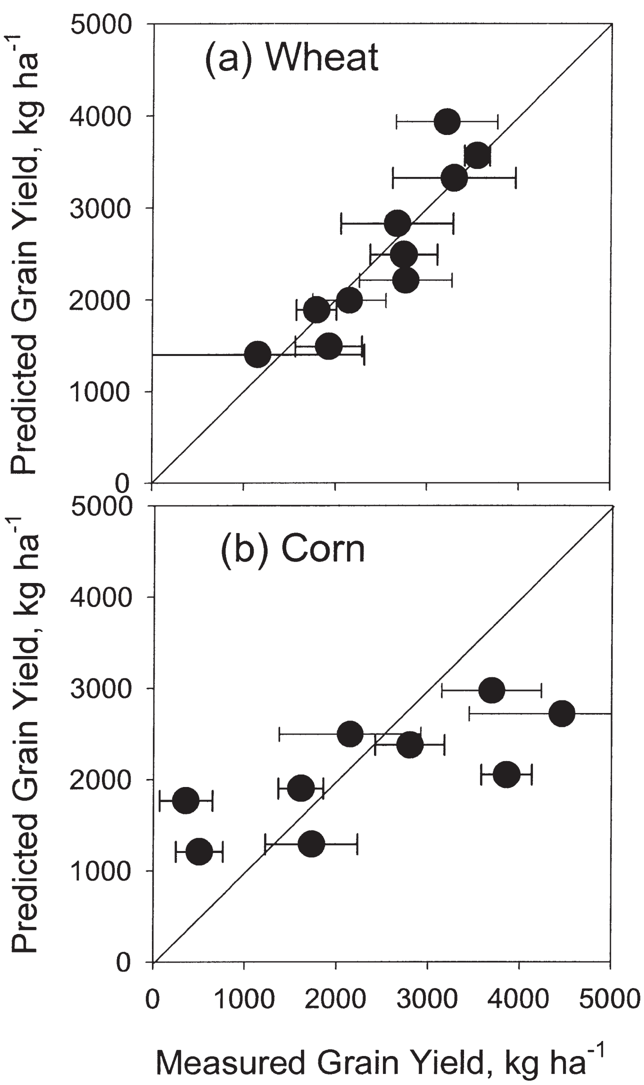

Fig. 8. Comparison between measured and predicted (RZWQM) wheat and corn grain yield for the wheat–corn–fallow (WCF) cropping system in the beginning wheat (WCF-W), beginning corn (WCF-C), and beginning fallow (WCF-F) data sets. Error bars show one standard deviation about the mean of measured yield.

Measured corn grain yields in the WCF data sets ranged from 357 to 4485 kg ha^{-1}. Predicted NT corn yields were relatively poorer (Fig. 8) compared with predicted wheat yields. High yields were underpredicted while low yields were overpredicted. Perhaps the model could have performed better if it had been recalibrated for dryland production. The calibration parameters used in the current study were taken from an irrigated corn study (Saseendran et al., 2005) with corn yielding 9700 kg ha^{-1}, well above the yield range observed in the current study. Additionally, the model likely needs improvement in how it handles yield reductions due to the timing of water stress in corn. Dryland corn yield response to available soil water and growing season precipitation is highly dependent on the amount of precipitation occurring from 15 July to 25 August (Nielsen et al., 1996). Precipitation during this critical time period was only 71 mm for the two lowest yield points in Fig. 8. The highest yield point in Fig. 8 was from a year with extremely high 15 July to 25 August precipitation (167 mm) and very low available soil water at planting (35 mm) while the next highest yield point was from a year with average 15 July to 25 August precipitation (96 mm) but very high available soil water at planting (126 mm).

Simulations of Biomass

In the WF data sets, total wheat biomass at harvest ranged from 2667 to 9961 kg ha^{-1} and was overpredicted by the model in 11 of the 16 yr (Fig. 9). Again, it is difficult to identify a single factor responsible for the large prediction errors due to the complex interactions among various model processes. The generally greater wheat biomass in NT compared with CT was not significant for either measured or predicted observations (Table 6).

In the WCF data sets, total wheat biomass at harvest ranged from 4239 to 9797 kg ha^{-1} and was significantly

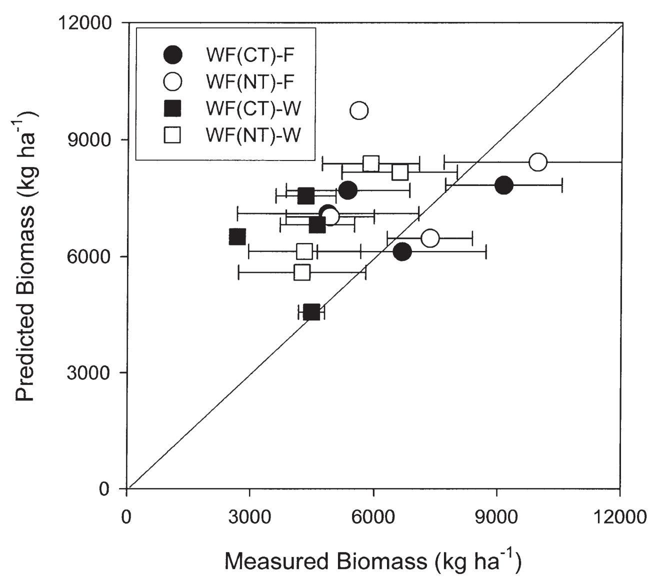

Fig. 9. Comparison between measured and predicted (RZWQM) wheat biomass for the wheat–fallow (WF) cropping systems in beginning fallow (WF-F) and beginning wheat (WF-W) data sets. Error bars show one standard deviation about the mean of measured biomass. CT, conventional till; NT, no-till.

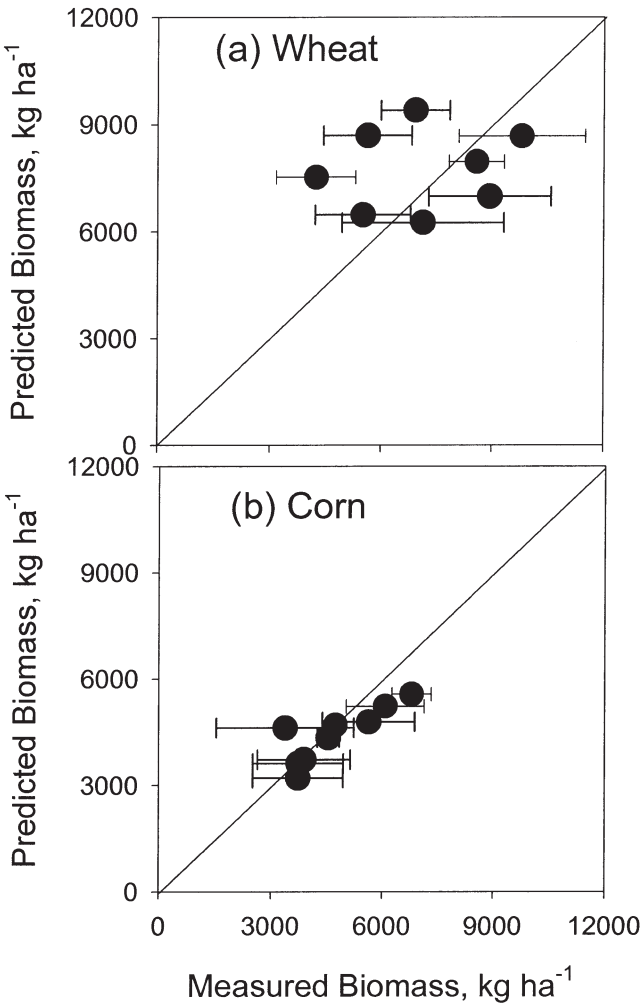

Fig. 10. Comparison between measured and predicted (RZWQM) wheat and corn biomass for the wheat–corn–fallow (WCF) cropping system in the beginning wheat (WCF-W), beginning corn (WCF-C), and beginning fallow (WCF-F) data sets. Error bars show one standard deviation about the mean of measured biomass.

overpredicted by the model in 3 of the 8 yr (Fig. 10). The prediction of wheat biomass for these data sets was better than for the WF data sets, as determined by the lower RMSE values (Table 3).

Total corn biomass at harvest in the WCF data sets ranged from 3385 to 6801 kg ha^{-1} and was well predicted by the model (Fig. 10). Biomass in 8 of 9 yr was predicted to within one standard deviation of measured biomass.

Simulations of Soil Organic Matter

Bowman et al. (1996) analyzed the data obtained from the Akron alternative crop rotation experiment from 1990 to 1995. They reported significantly more (14%) SOM in NT than in CT in the 0- to 5-cm soil layer. RZWQM simulations showed SOC from 1992 to 2001 declining 10.6% in WF(CT), increasing 13.8% in WF(NT), and increasing 19.3% in WCF(NT) (Table 7). At the end of the 10-yr simulation period, SOC was nearly 20% higher in WCF(NT) compared with WF(CT) (10 817 vs. 9048 μg g^{-1}).

Table 7. RZWQM-predicted change in total soil organic carbon (SOC) between first planting date in 1992 to the last planting date in 2001 (0 to 10 cm) due to different cropping systems.

Data set†	Beginning SOC 0–10 cm	Ending SOC 0–10 cm	Percentage change in SOC
	μg g^{-1}		%
WF(CT)-W	9 587	9 164	−4
WF(CT)-F	10 734	8 931	−17
Average for WF(CT)	10 161	9 048	−11
WF(NT)-W	8 624	9 815	14
WF(NT)-F	8 633	9 819	14
Average for WF(NT)	8 629	9 817	14
WCF(NT)-W	9 096	10 659	17
WCF(NT)-C	9 060	10 910	20
WCF(NT)-F	9 049	10 883	20
Average for WCF(NT)	9 068	10 817	19

† WF(CT)-W = conventionally tilled wheat–fallow beginning with the wheat phase; WF(CT)-F = conventionally tilled wheat–fallow beginning with the fallow phase; WF(NT)-W = no-till wheat–fallow beginning with the wheat phase; WF(NT)-F = no-till wheat–fallow beginning with the fallow phase; WCF(NT)-W = no-till wheat–corn–fallow beginning with the wheat phase; WCF(NT)-C = no-till wheat–corn–fallow beginning with the corn phase; WCF(NT)-F = no-till wheat–corn–fallow beginning with the fallow phase.

CONCLUSIONS

We tested and validated RZWQM for its ability to simulate crop rotations involving winter wheat, corn, and fallow under CT and NT management. The simulations reasonably predicted differences in soil water, crop grain yield, and C sequestration for both tillage practices in WF and in NT WCF cropping systems. Predicted soil water, grain yield, biomass, and ET were in reasonably good agreement with measured values. The LAI predictions showed greater deviations from measured values, but we did not have enough LAI measurements for detailed analysis. Model simulations over the 10-yr period showed greater SOC sequestration in the 0- to 10-cm soil layer in the NT system compared with CT systems. Simulations also showed that soil C sequestration increased with increased cropping intensity. We conclude that the generic crop model of RZWQM needs improvement for more accurate simulations of plant growth and development, with emphasis on improving biomass, ET, and LAI predictions. Despite the inaccuracies of the current model, we conclude that the model has reasonable potential for quantifying and synthesizing research findings from alternative crop rotation system experiments in the Great Plains and for extending the results to other soils, climates, and management practices.

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